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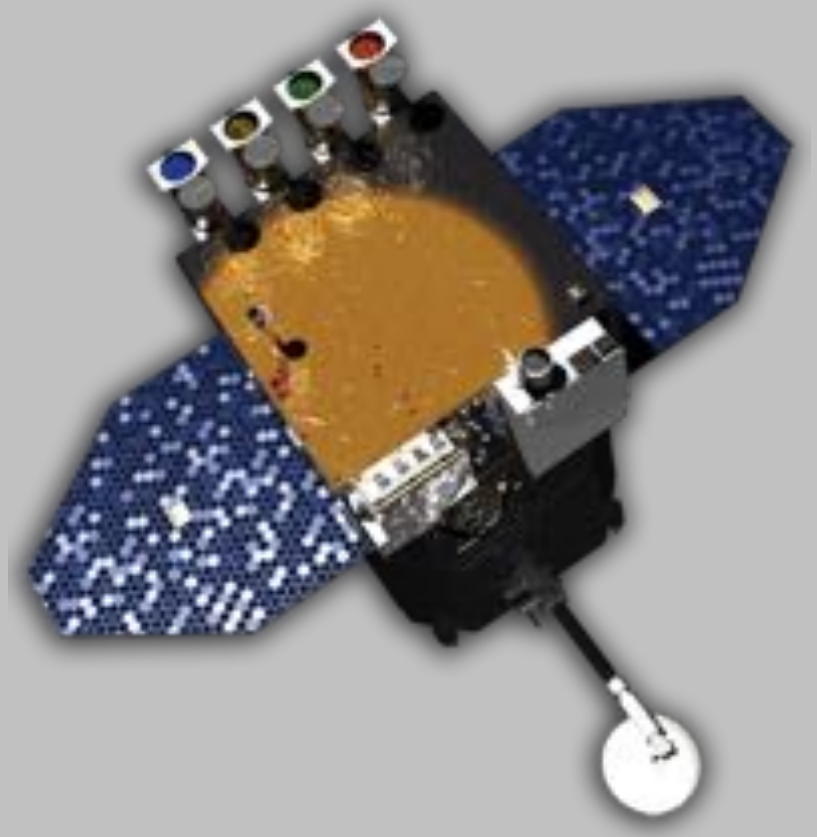
Solar Cycle Predictions



W. Dean Pesnell

NASA, Goddard Space Flight Center

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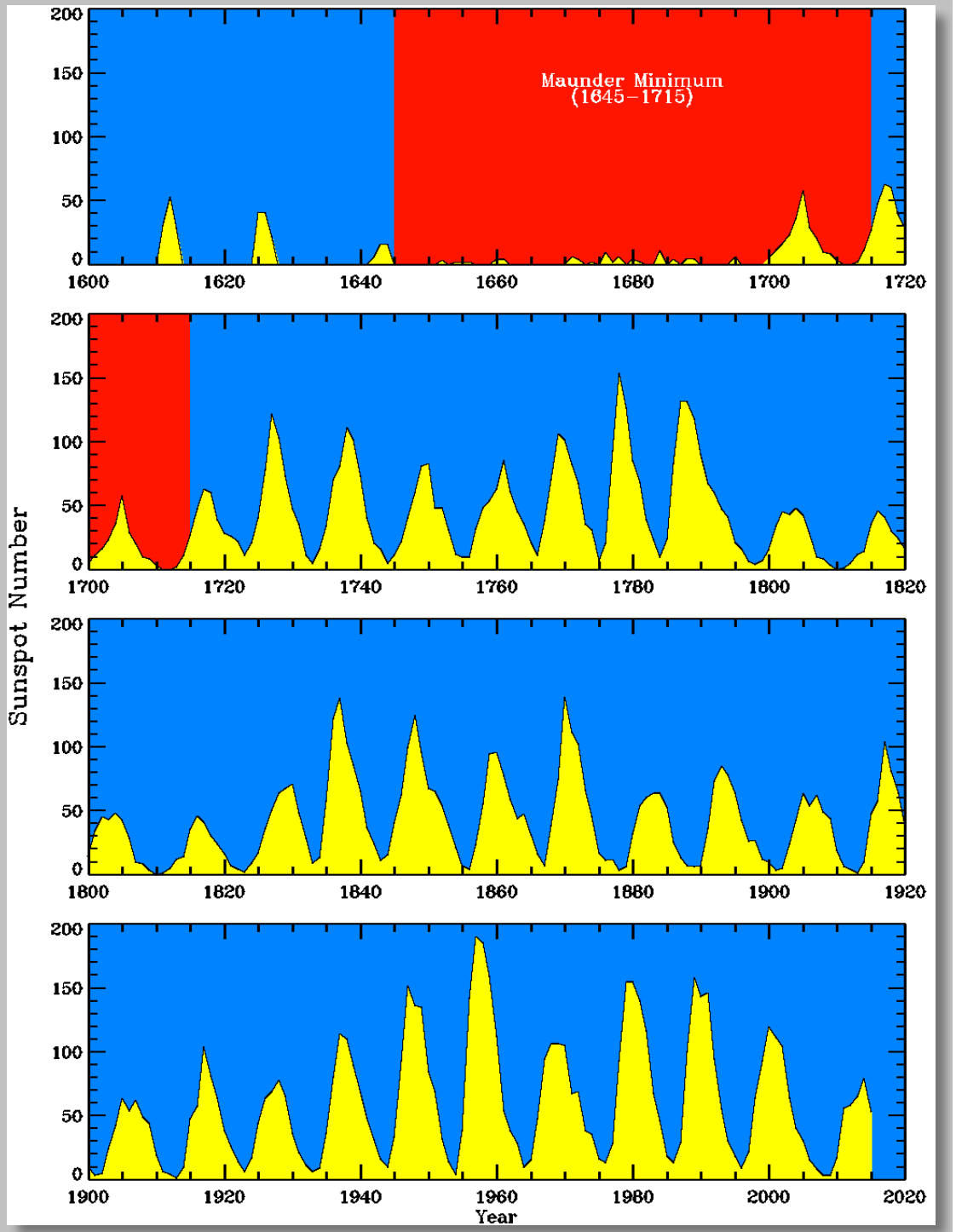
What should Space Weather predict?

What kinds of predictions are there?

For long-term work we usually report predictions of sunspot number (R_Z).

How well have we done at predicting R_Z?

What can we do better?



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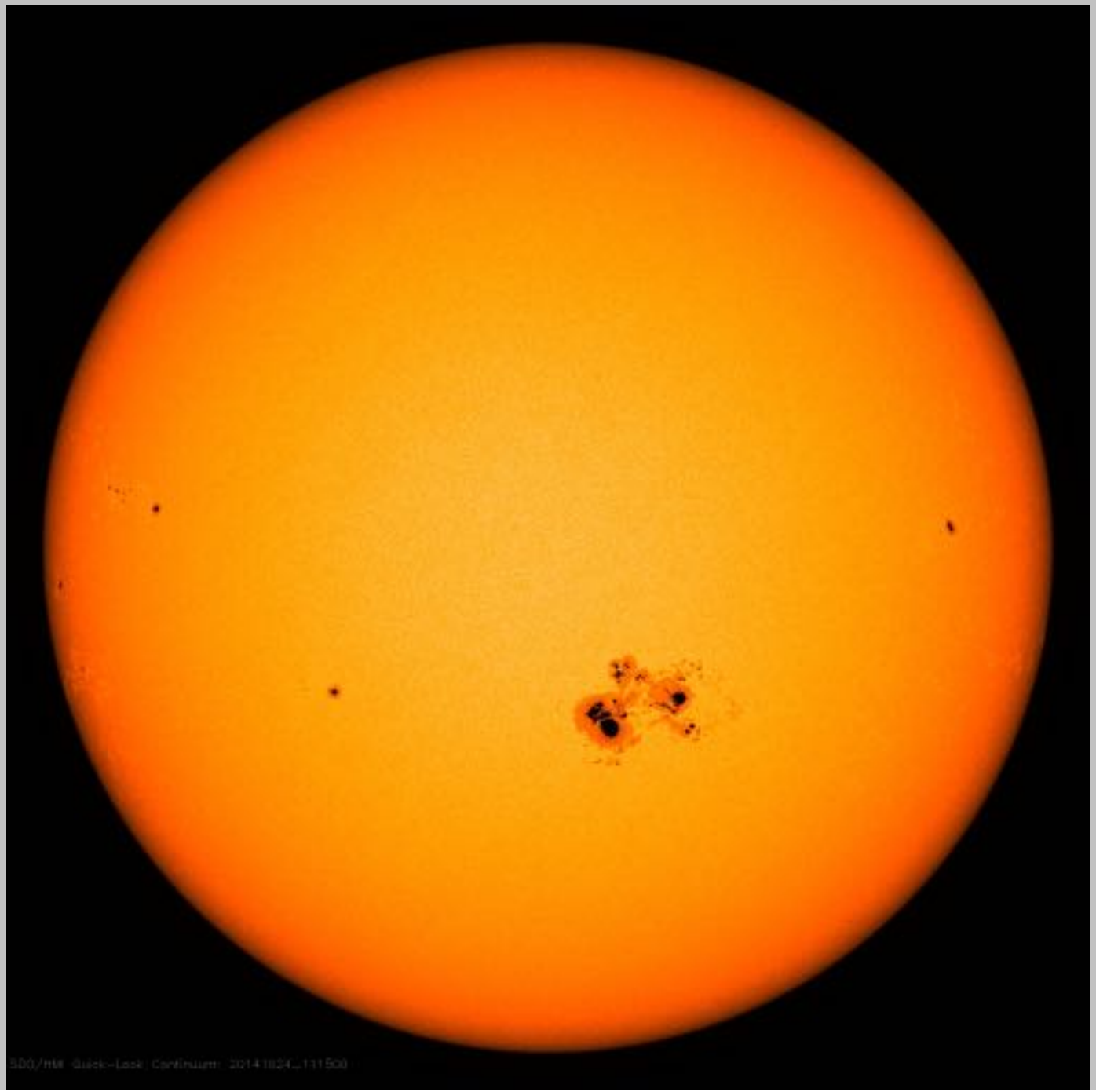
What is a Sunspot?

$R_Z = 93!$



HMI Image with AR 12192 from 24-Oct-2014.

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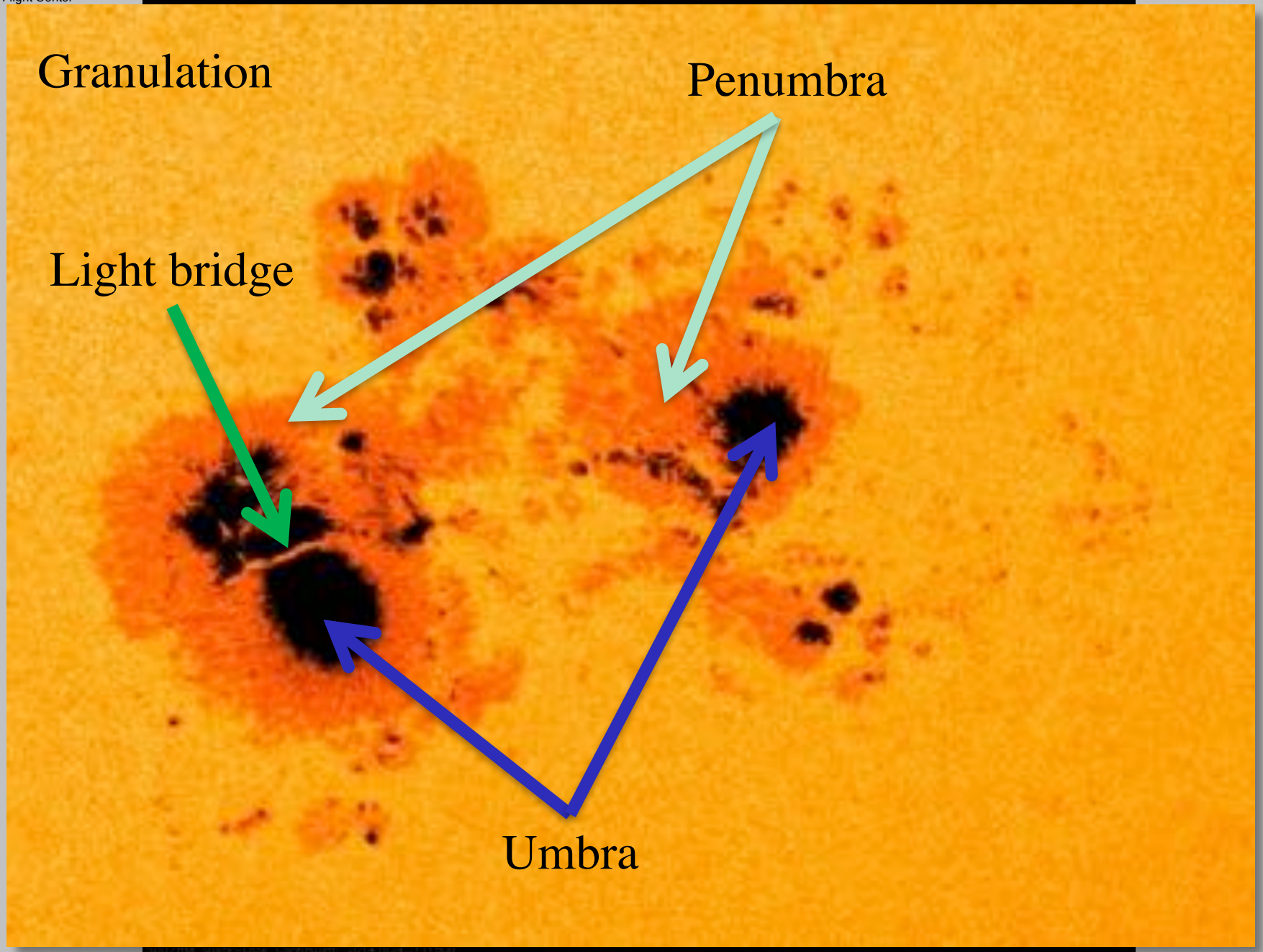
What is a Sunspot?



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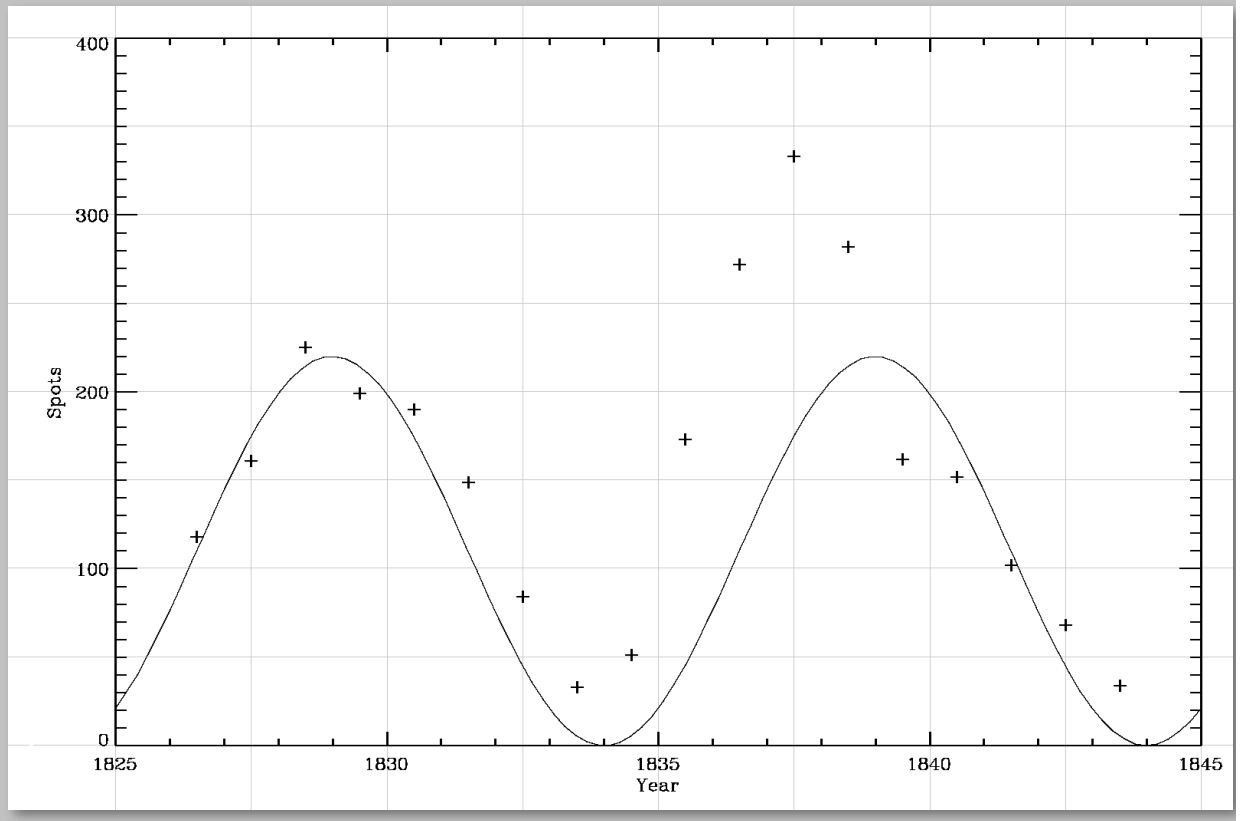
First Prediction was at Discovery

Samuel Heinrich Schwabe
(Dessau, 1789–1875)

Schwabe noted a 10-year period in his observed sunspot count.



He also noted that sunspot number should increase if he was correct. “The next few years will show whether or not this period persists in the sunspot record.”

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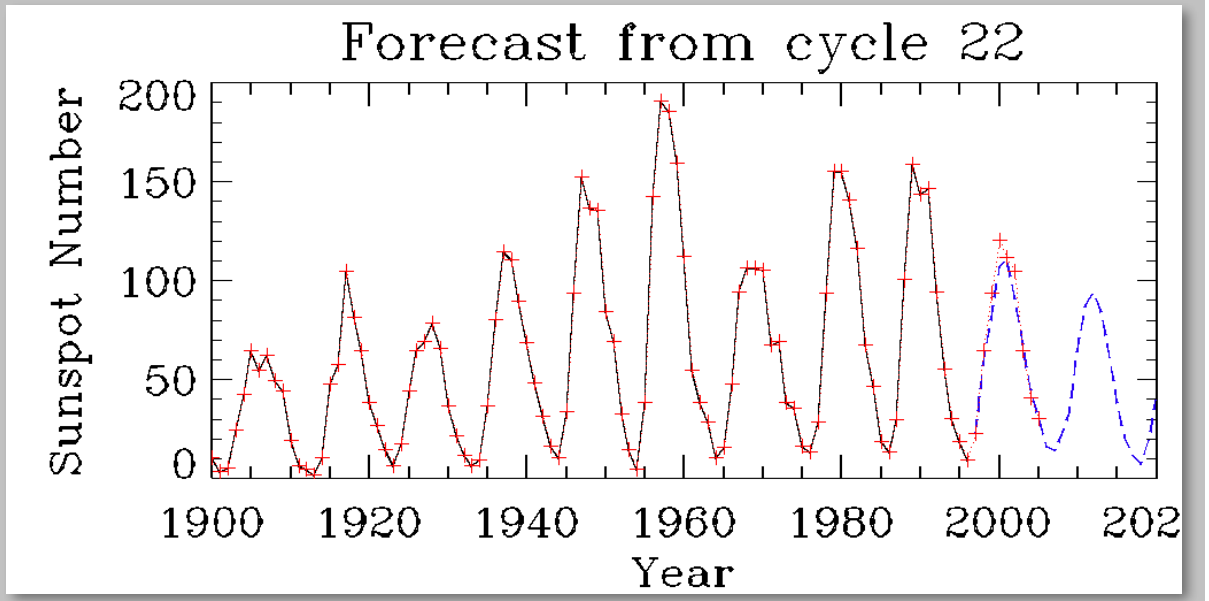
Mathematicians like Predictions

George Udny Yule, 1871-1951

Yule treated R_Z as data to test prediction techniques. He developed autoregression to predict R_Z better than periodograms.



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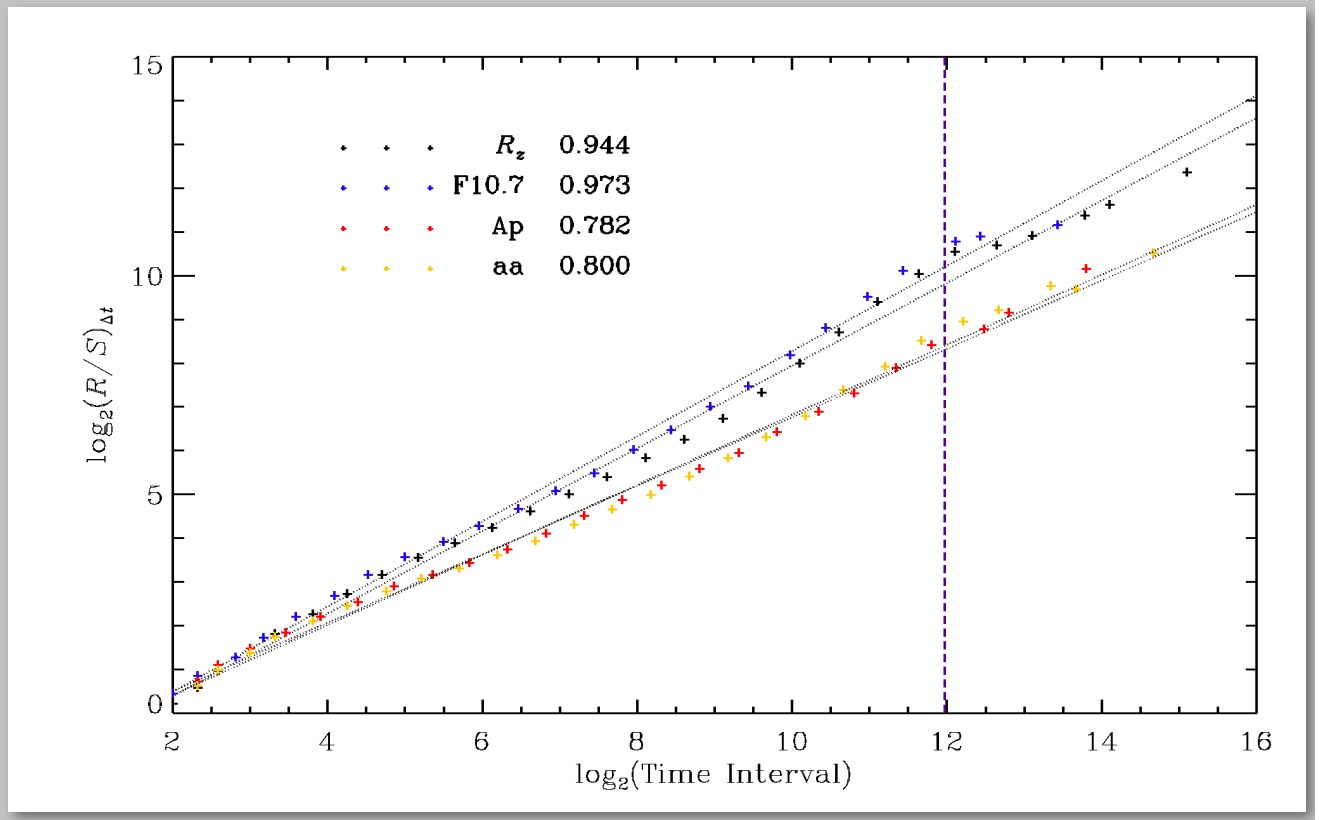
Chaos ≠ Unpredictable

Benoit Mandelbrot, 1924-2010

Mandelbrot and collaborators used R_Z as data to test chaos-oriented prediction techniques. He showed R_Z can be predicted better than white noise (Hurst exponent of white noise is 0.5.)



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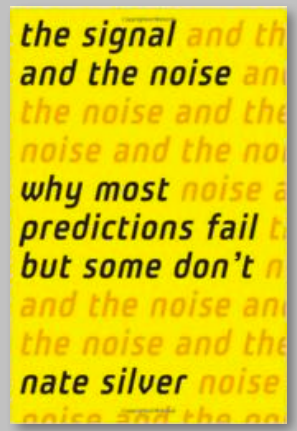
What Kinds of Predictions?

- Climatological (statistical): Future is an average of the past
  - One example: The upcoming solar maximum will be 115 ± 40, the long-term average of all prior maxima
  - Should be obsolete!
- Spectral: Evolution of Fourier coefficients



- Precursor: Look for other variables that are leading indicators of activity
  - Polar magnetic field at minimum ~ level of activity at next maximum
  - Flares are anticipated by the appearance of a sigmoid
- Physics-based models: Forecasts produced by models capable of integrating conservation equations, possibly using data-assimilation

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What Kinds of Forecasts?

- When called technical analysis, charting, statistical, spectral, and leading indicators, the first three are used in stock market prediction and other economic forecasting.

- What sets the solar cycle apart is an underlying system that can be represented by a physics-based model

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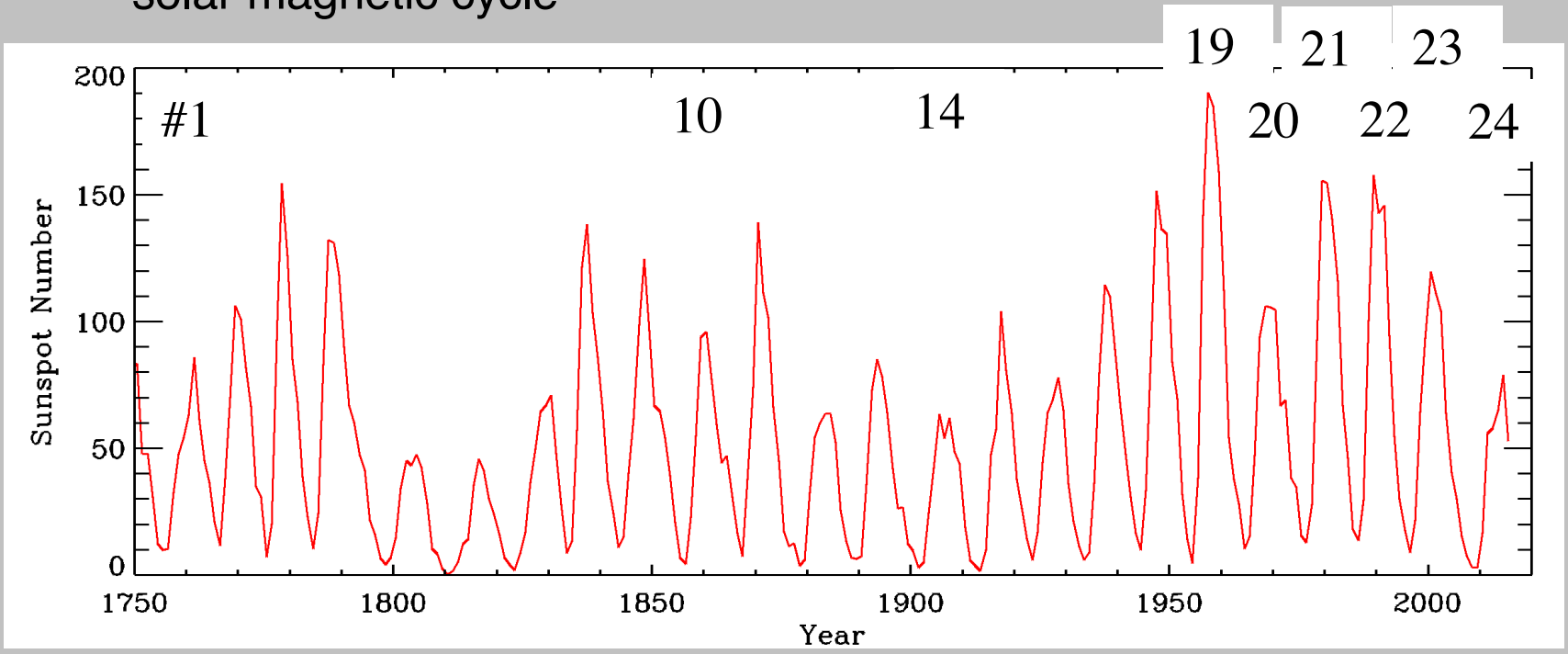
Two Statistical Forecasts

- The inertial forecast, $x_{n+1} = x_n$, is familiar from weather forecasts: Tomorrow will be the same as today.
- The even-odd forecast, $x_{n+1} = x_{n-1}$, comes from noticing that the sunspot cycle is similar not to the current cycle but to the previous one.
  - Related to the magnetic field flipping twice to form a complete 22-year solar magnetic cycle



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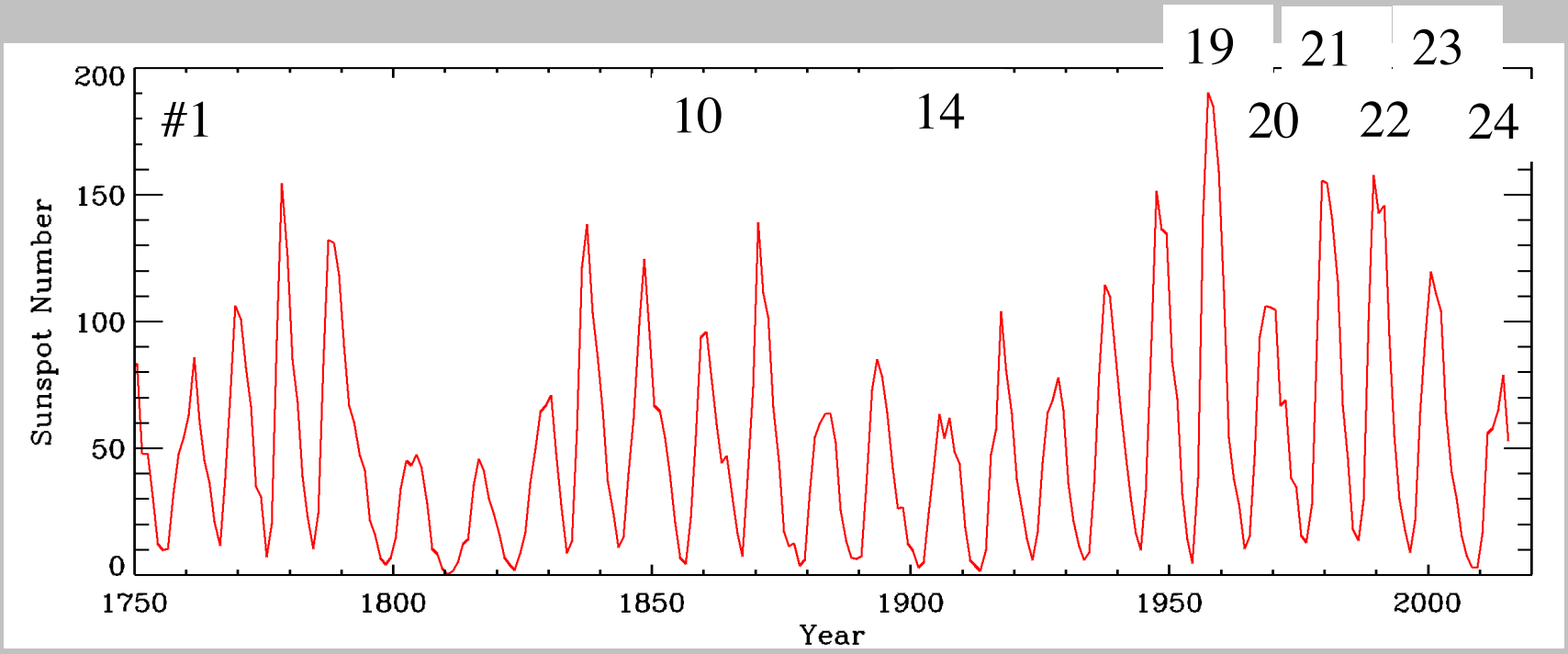
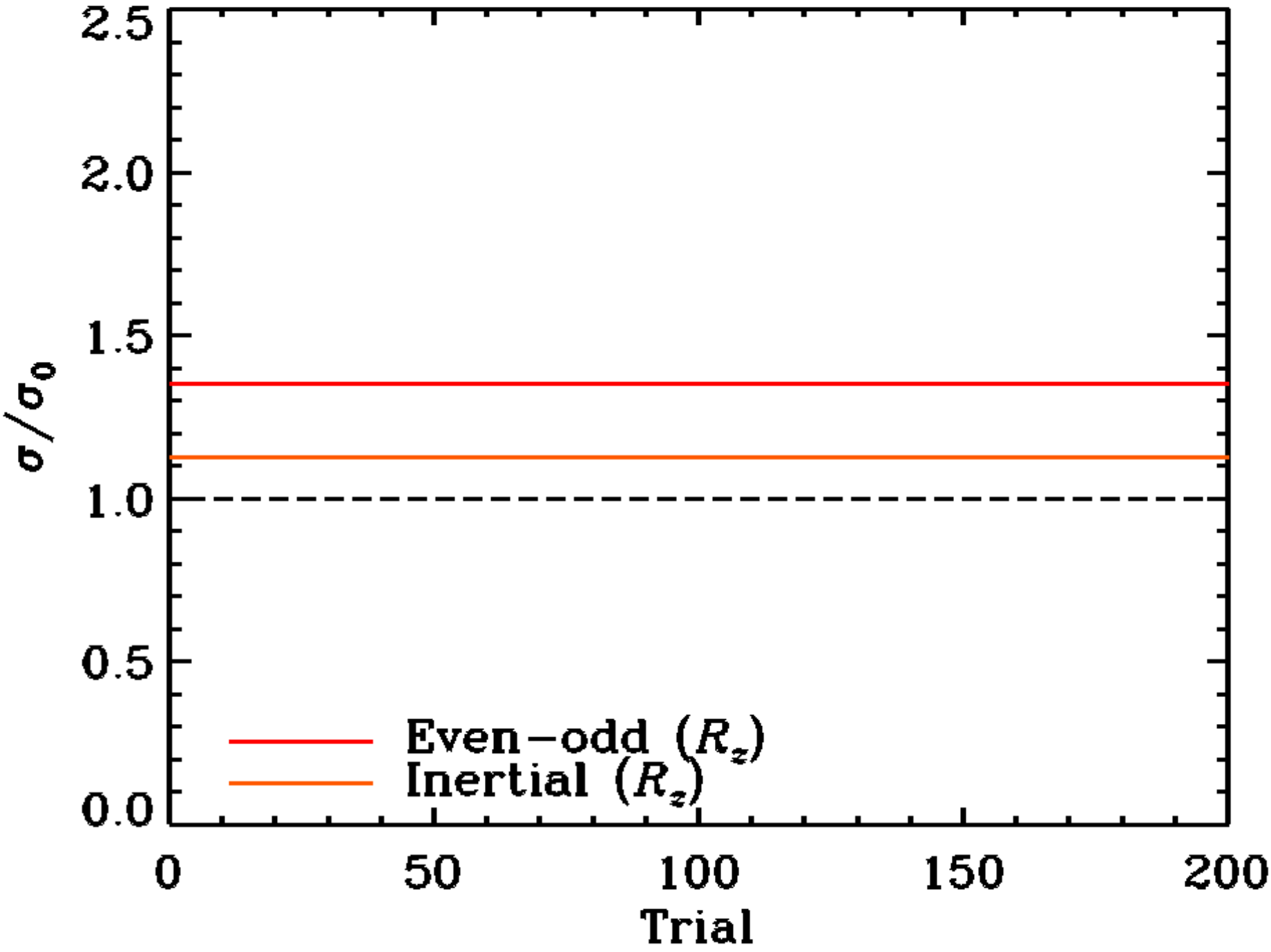
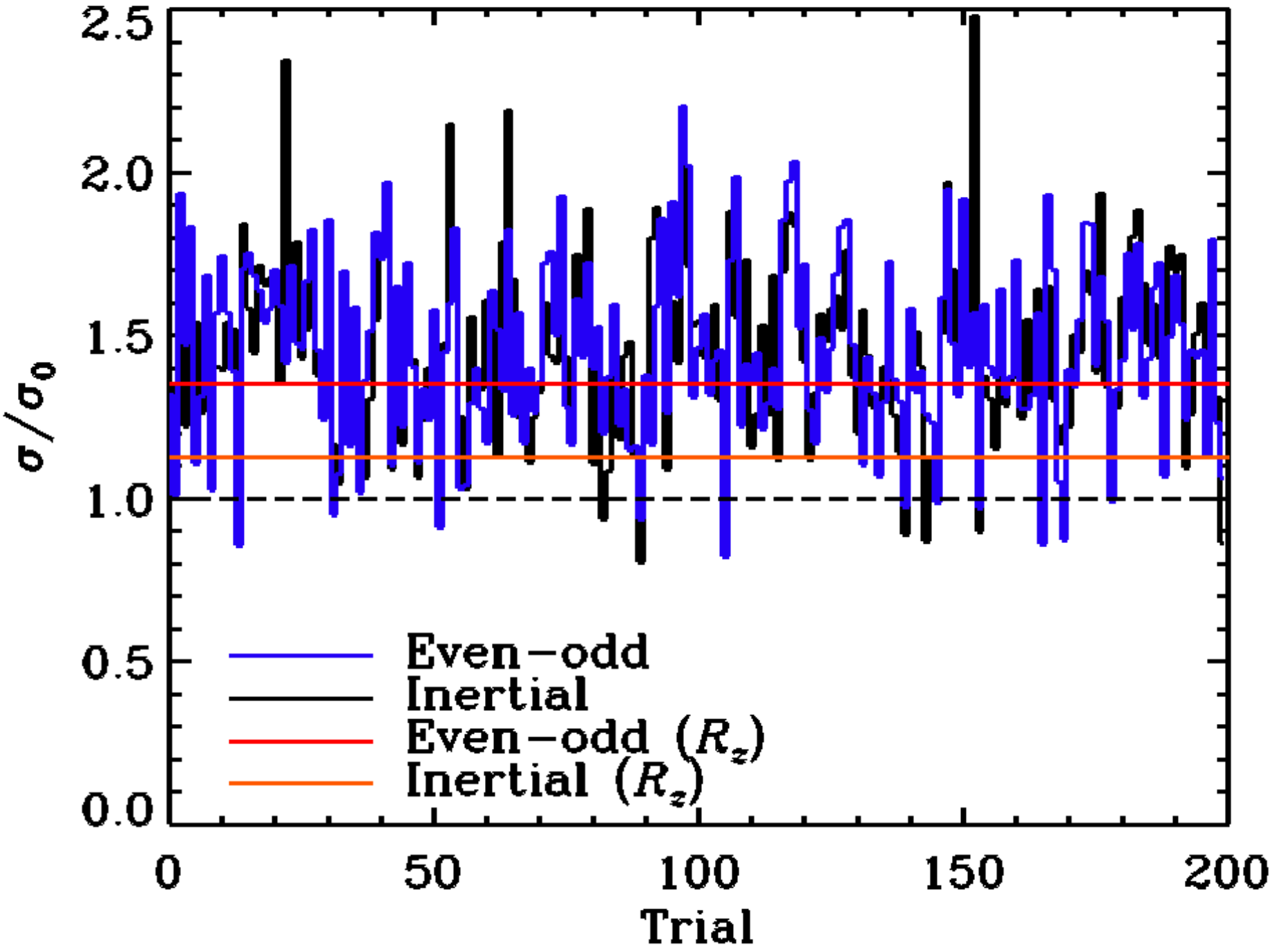
Two Statistical Forecasts

- Run the inertial and even-odd forecasts over the historical data set and compare with the average and standard deviation of the peaks




2.5
2.0
1.5
1.0
0.5
0.0
σ/σ0
0
50
100
150
200
Trial
Even−odd (Rz)
Inertial (Rz)


2.5
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σ/σ0
0
50
100
150
200
Trial
Even−odd
Inertial
Even−odd (Rz)
Inertial (Rz)

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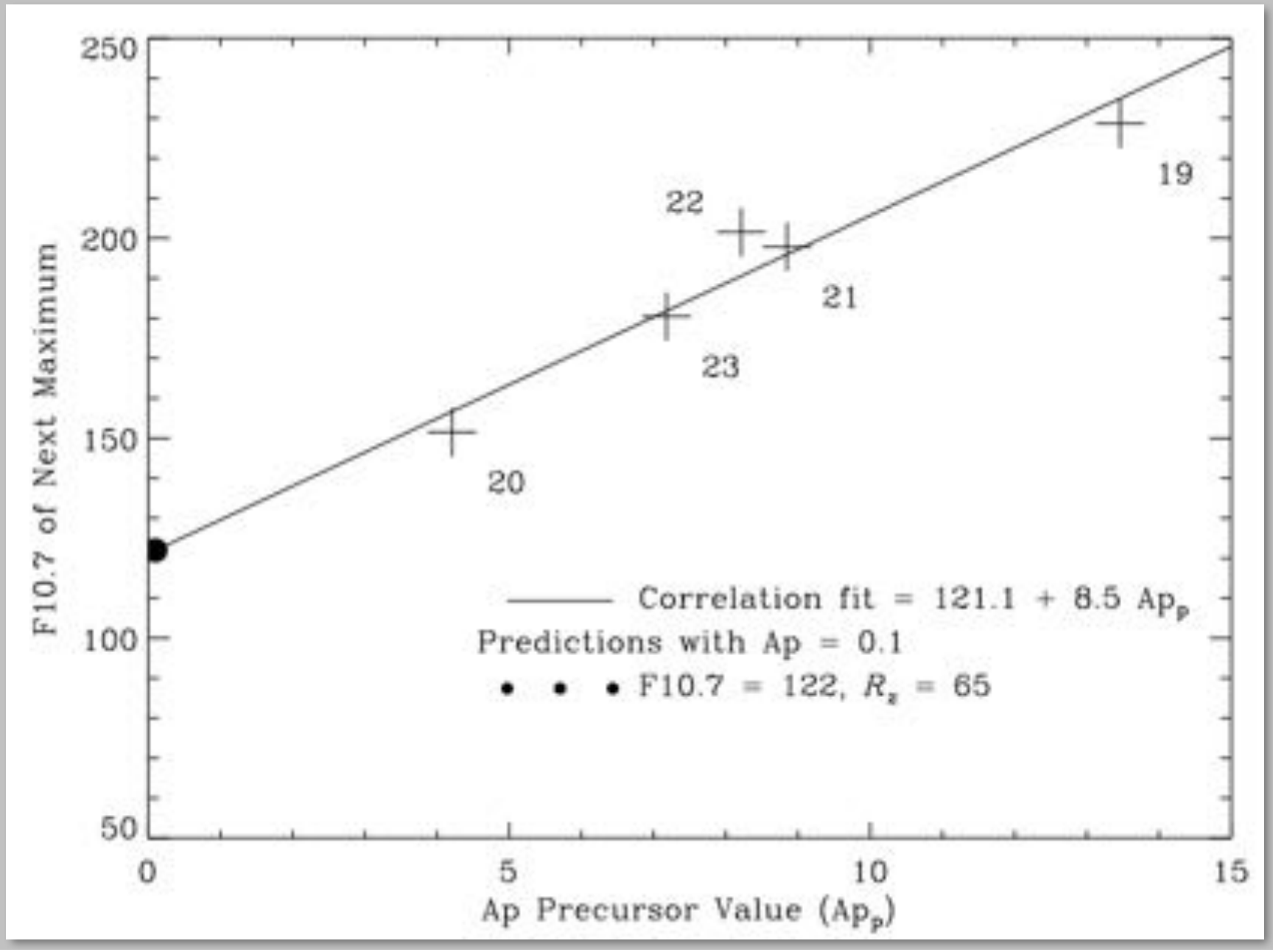
Geomagnetic Precursor Pair, Ap and F10.7



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What Else Should We Predict?

- Sunspot Number
  - Long-term dataset of varying quality
  - Proxy for many other indexes, merges onto the radionuclide record
  - Poor linkage in internal dynamo processes
- Magnetic Field
  - Determines solar activity
  - Only have global data for the last few sunspot cycles
- Convection zone dynamics, F10.7, Ap, flare occurrence, filament eruptions
  - Wide range of timescales for predictions
  - Wide range of users (data latency, sensitivity to false alarms)

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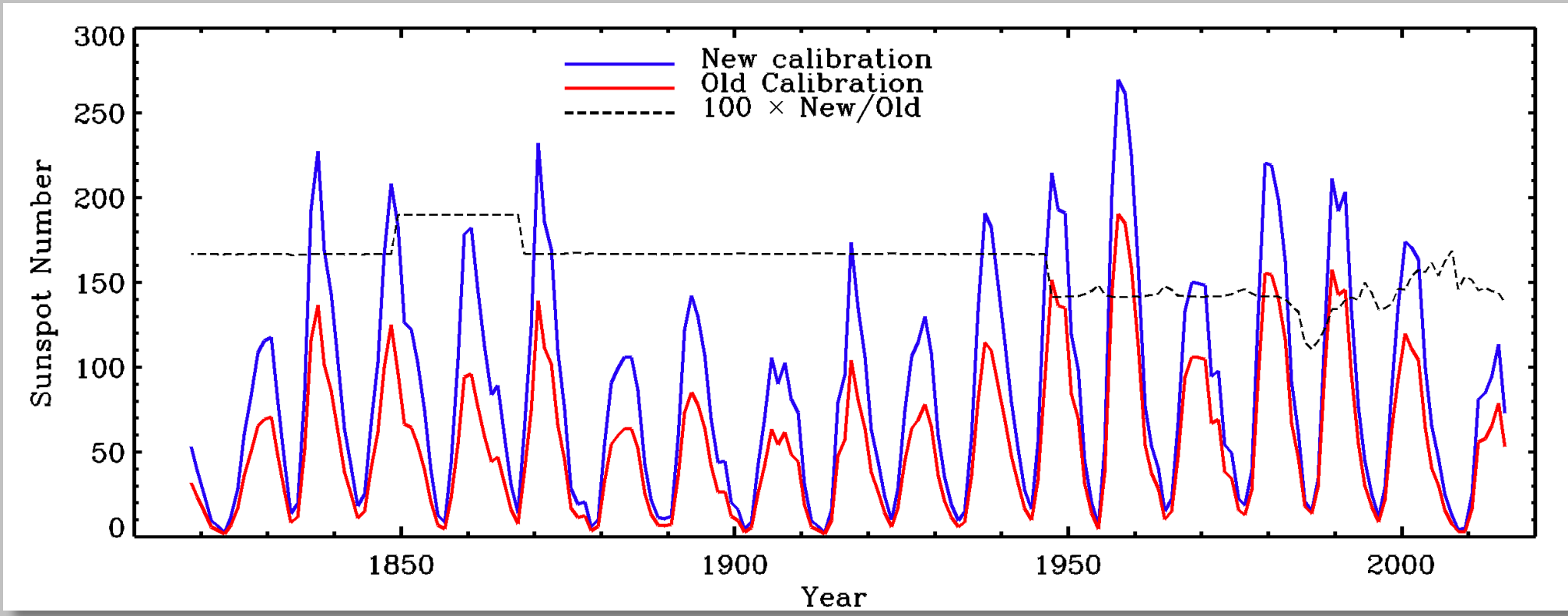
Sunspot Number vs. Sunspot Number



Nothing gets scientists going like a good recalibration. We are revising the sunspot number but our next round of predictions will have contributions using both V1, V2, and many others.

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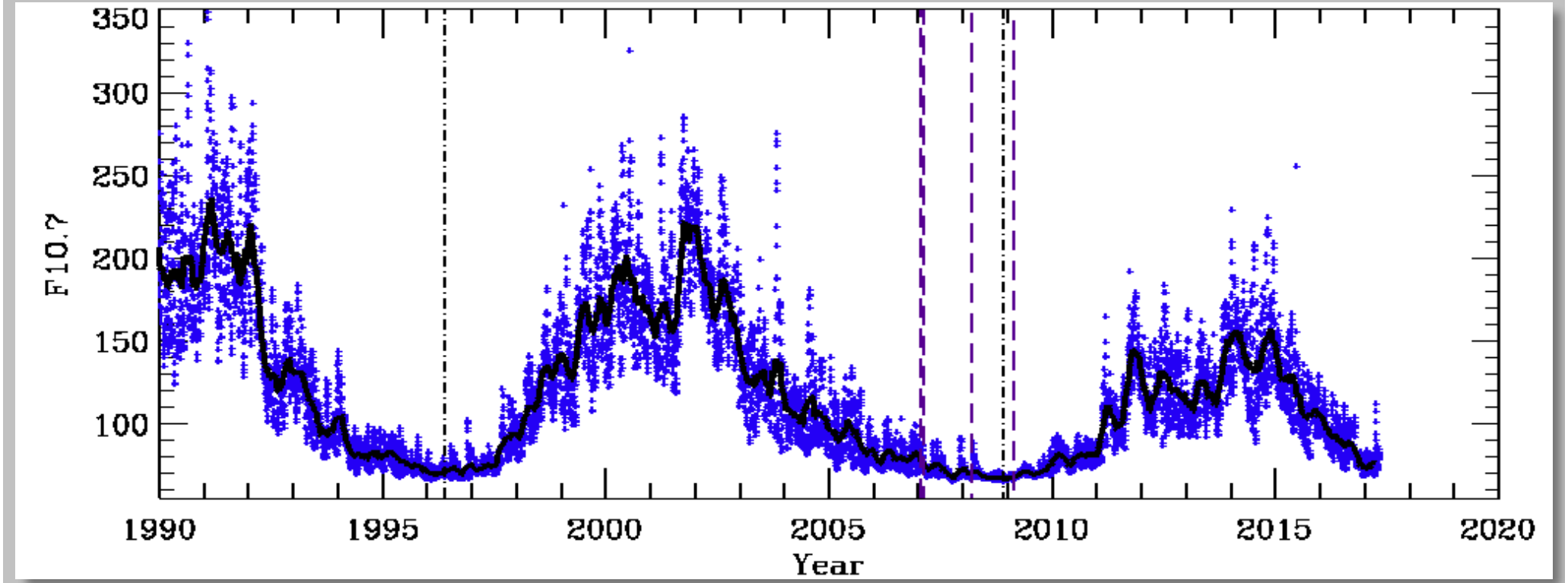
F10.7: Solar Spectral Irradiance at 10.7 cm



F10.7 has been reported almost daily since 1947. The advantage over R_Z is the rapid availability. Final values of R_Z are delayed up to a month. Satellite operators can't wait! Here are the daily and 81-day averages since 1990, along with 4 debris issues, Febgyun-1C, Briz-M, Cosmos 2421, and Iridium 33/Cosmos 2251.

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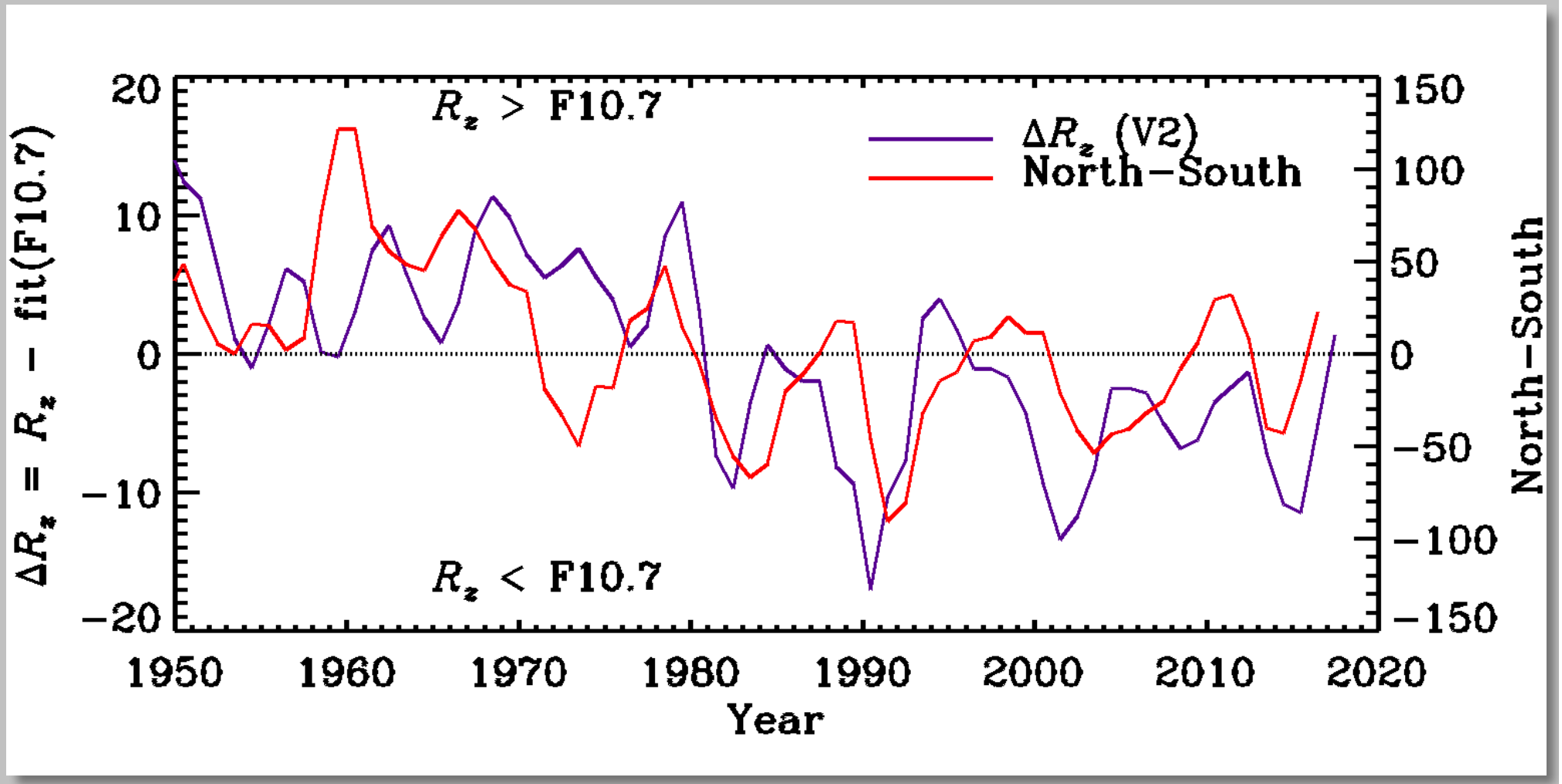
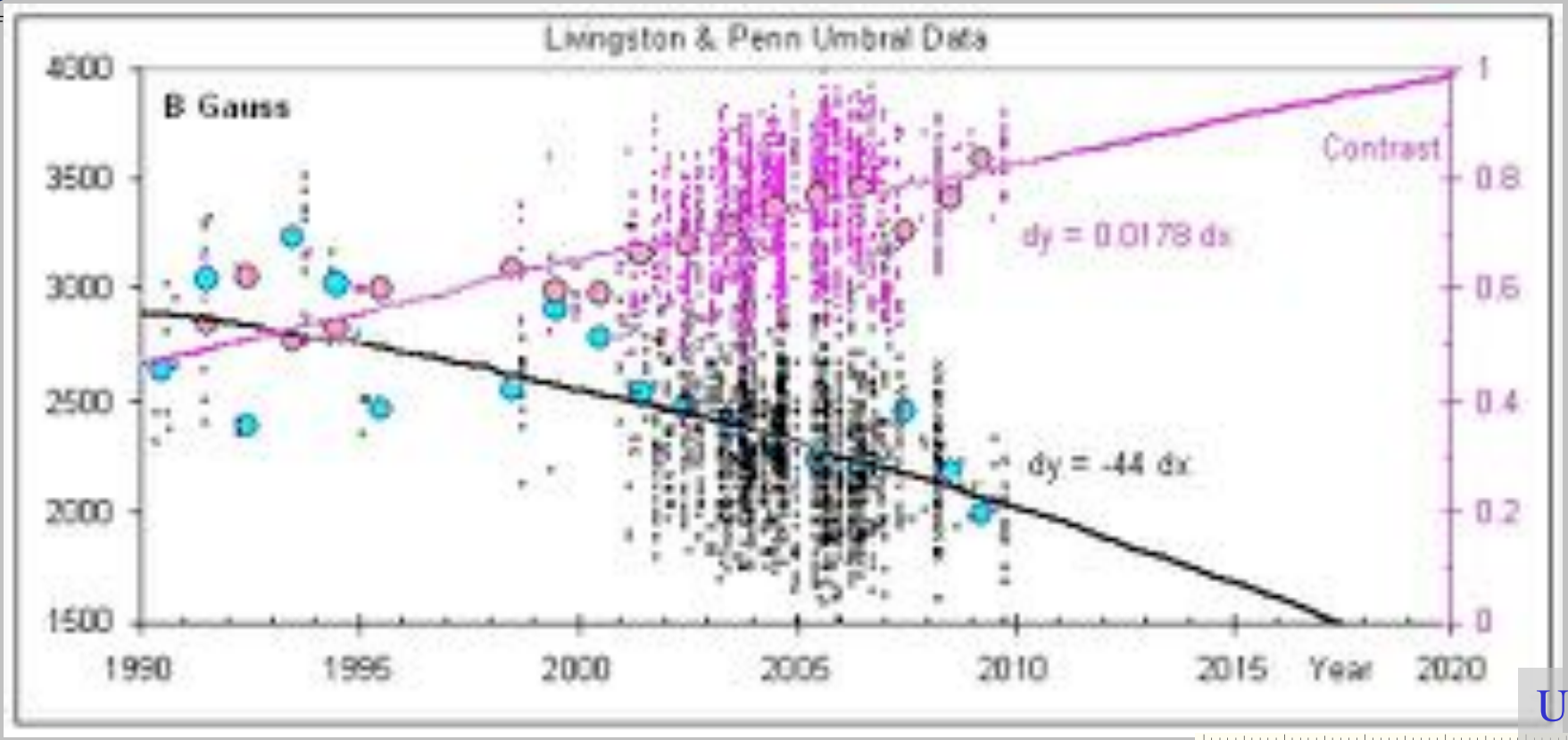
Sunspot Number and F10.7

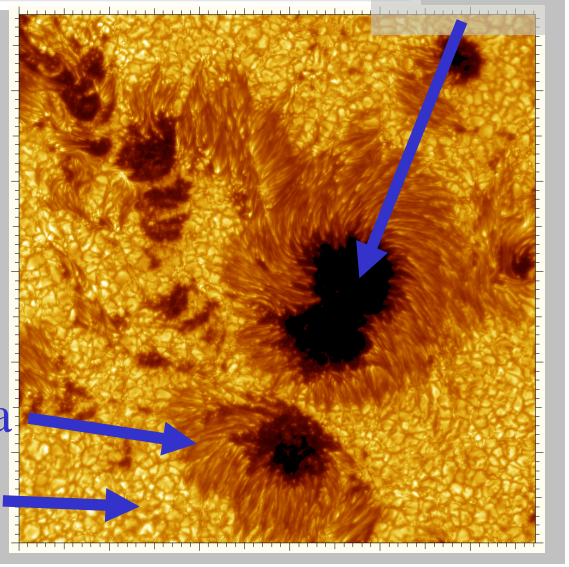


Residual of the fit between R_Z and F10.7 (in blue.) The tendency of R_Z to be smaller than F10.7 may be fixed by V2. The North-South asymmetry in the number of active regions is shown as a solid red line. There is slight correlation between the two curves.

Are Sunspots Fading Away?



Livingston and Penn have studied the magnetic field and umbra/photosphere contrast ratio in sunspots since the maximum of Solar Cycle 22. The magnetic field in the umbral region has been decreasing while the umbra is also fading into the photosphere. Newer studies seem to show it varies with activity.



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How Well Have We Done?

- Solar Cycles 20, 21, 22, 23, and 24 have had a large variety of predictions made.

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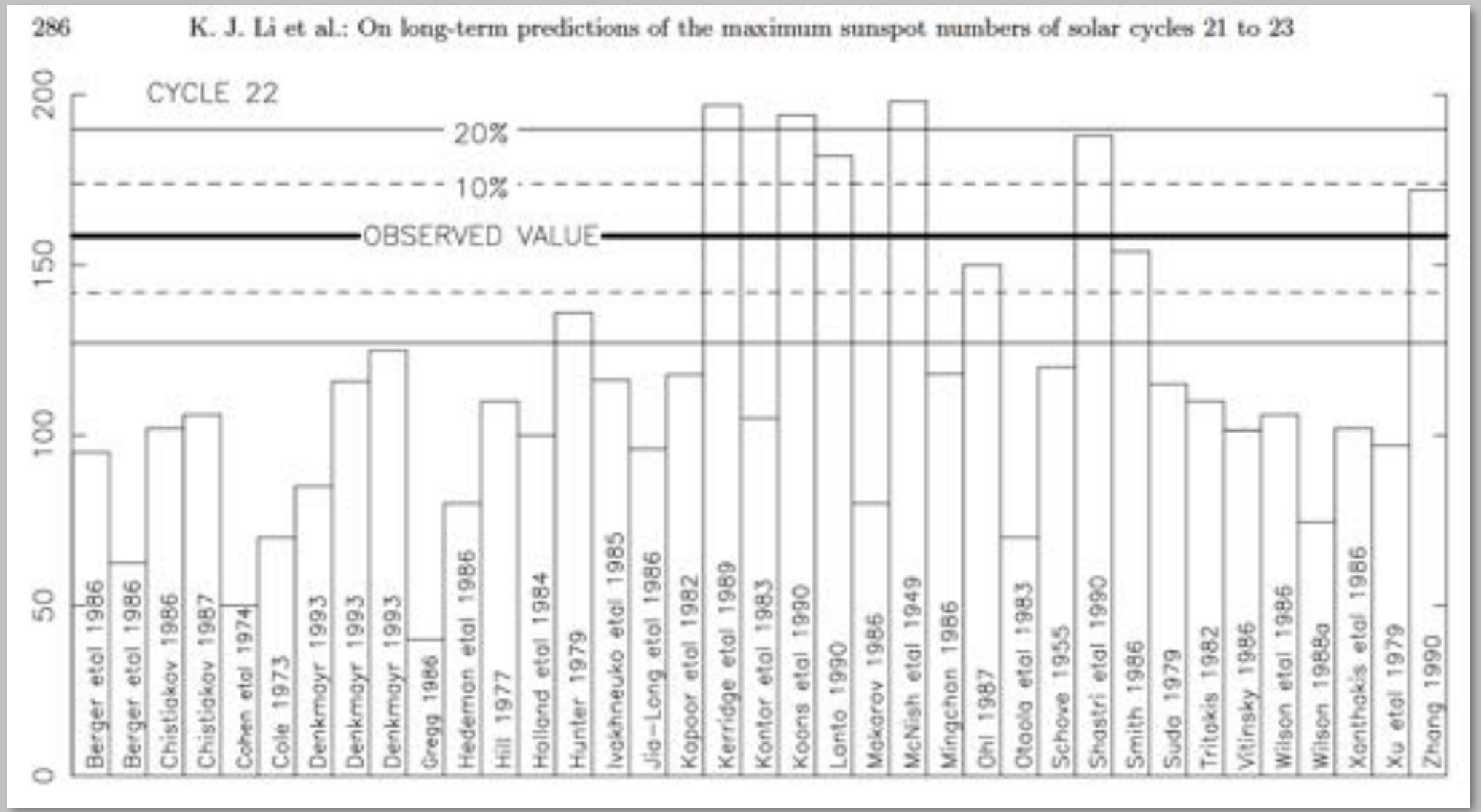
Solar Cycle 22



Climatological forecasts tended to be too small.

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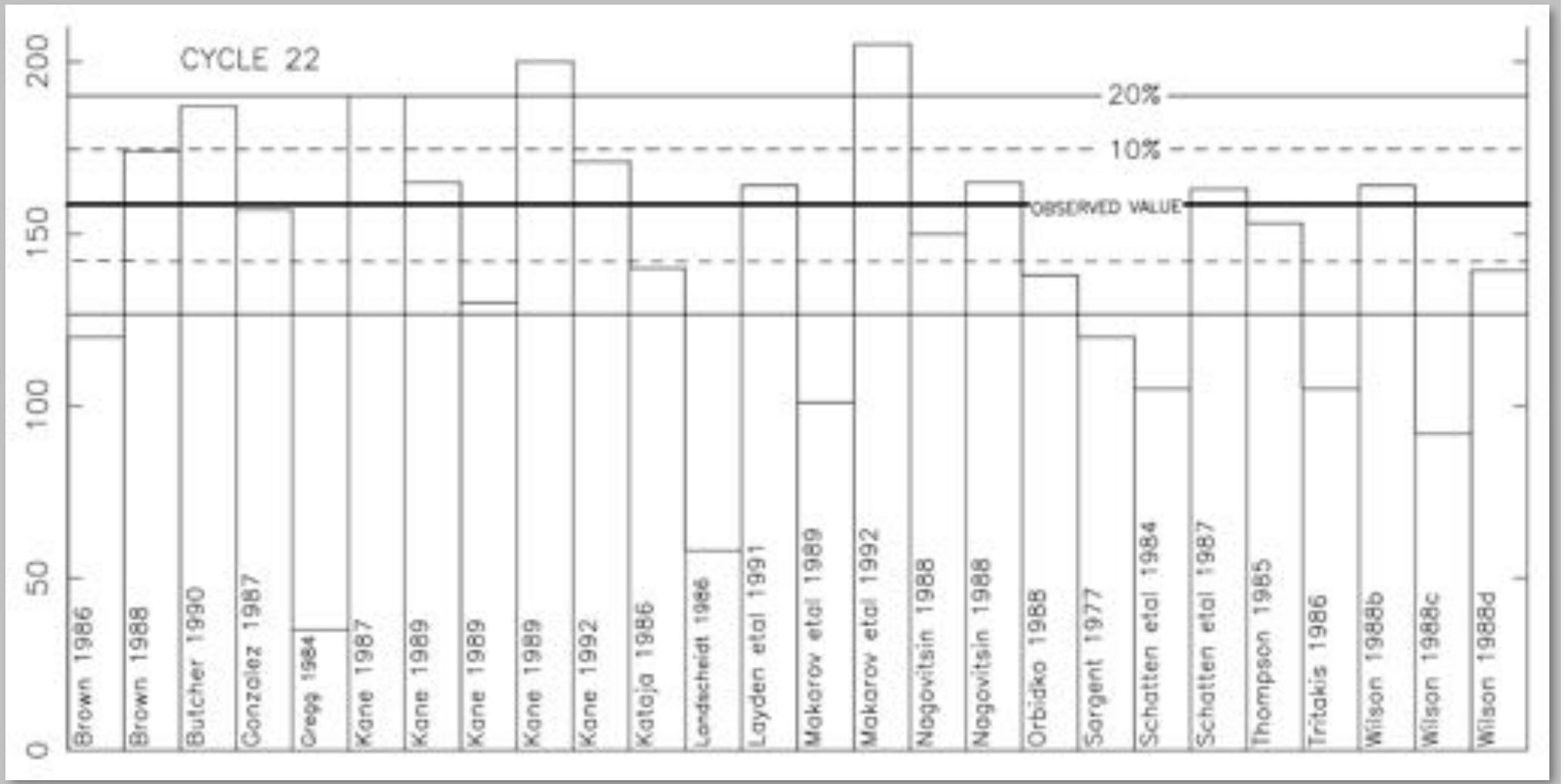
Solar Cycle 22



Precursor forecasts tended to surround the actual values.

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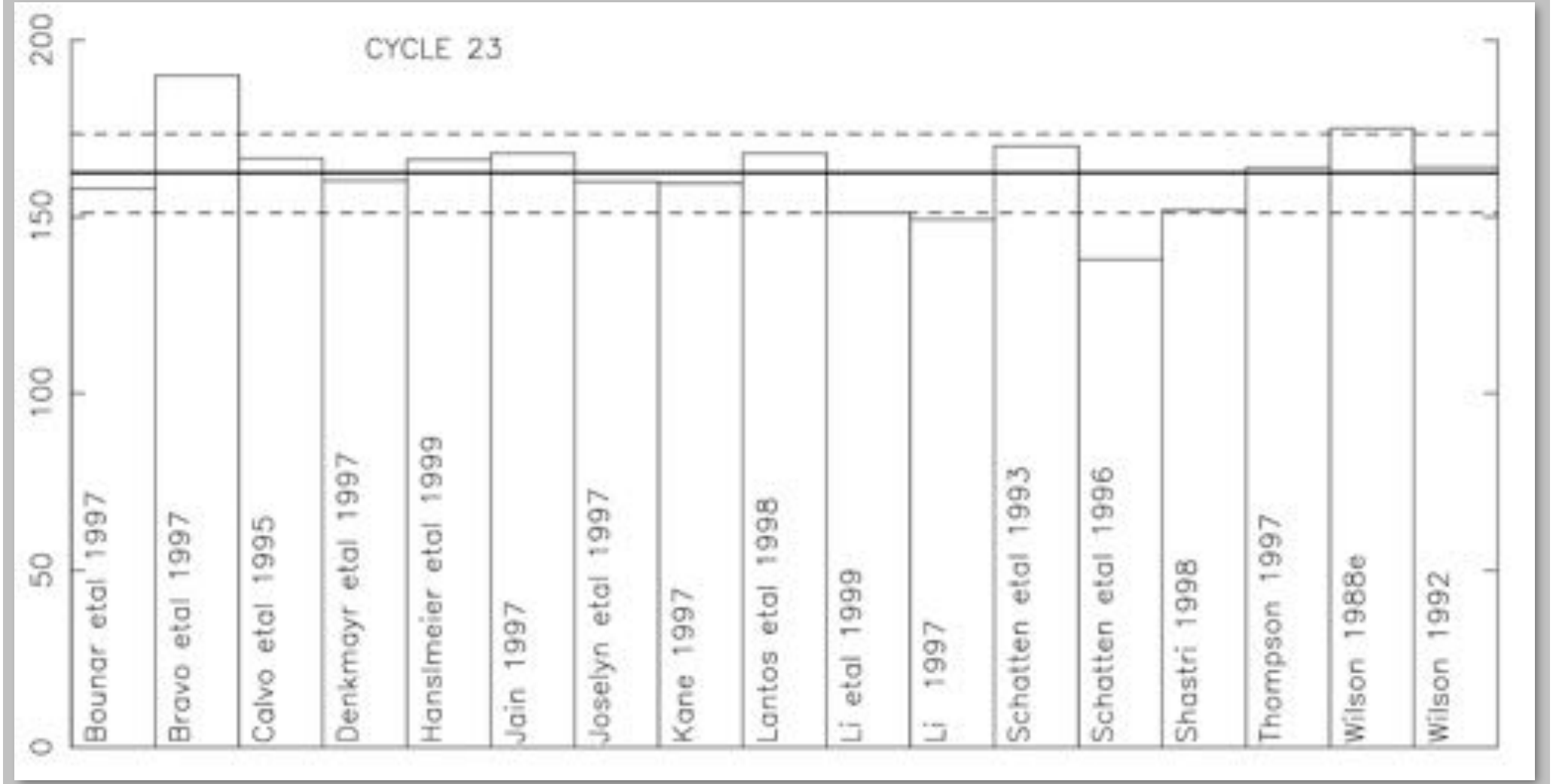
Solar Cycle 23



While climatological forecasts still had a large scatter, the precursor forecasts tended to more closely group around the actual value.

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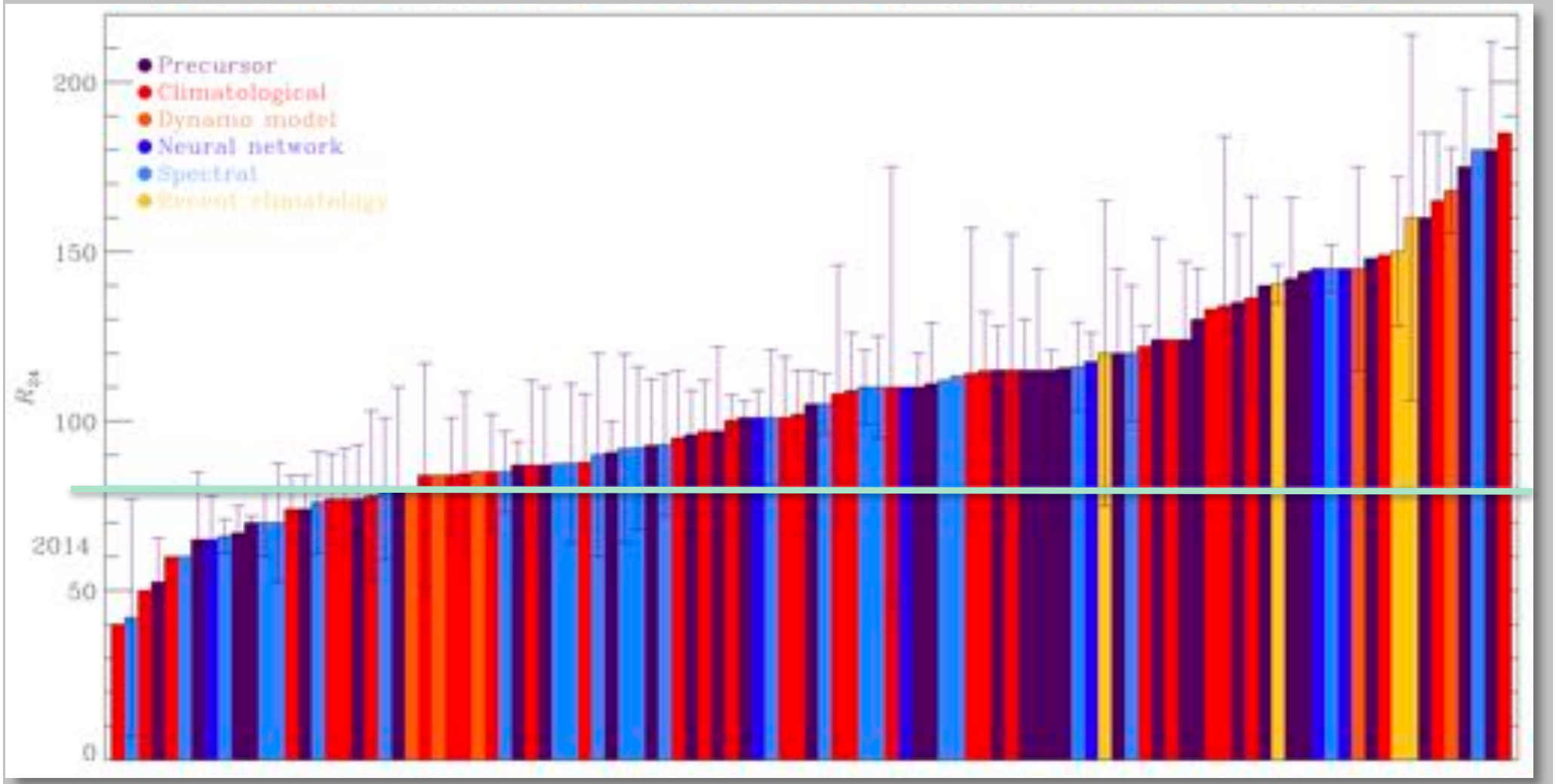
How Active Will Solar Cycle 24 Be?



The 105 predictions for Solar Cycle 24 foretold a wide range possibilities.

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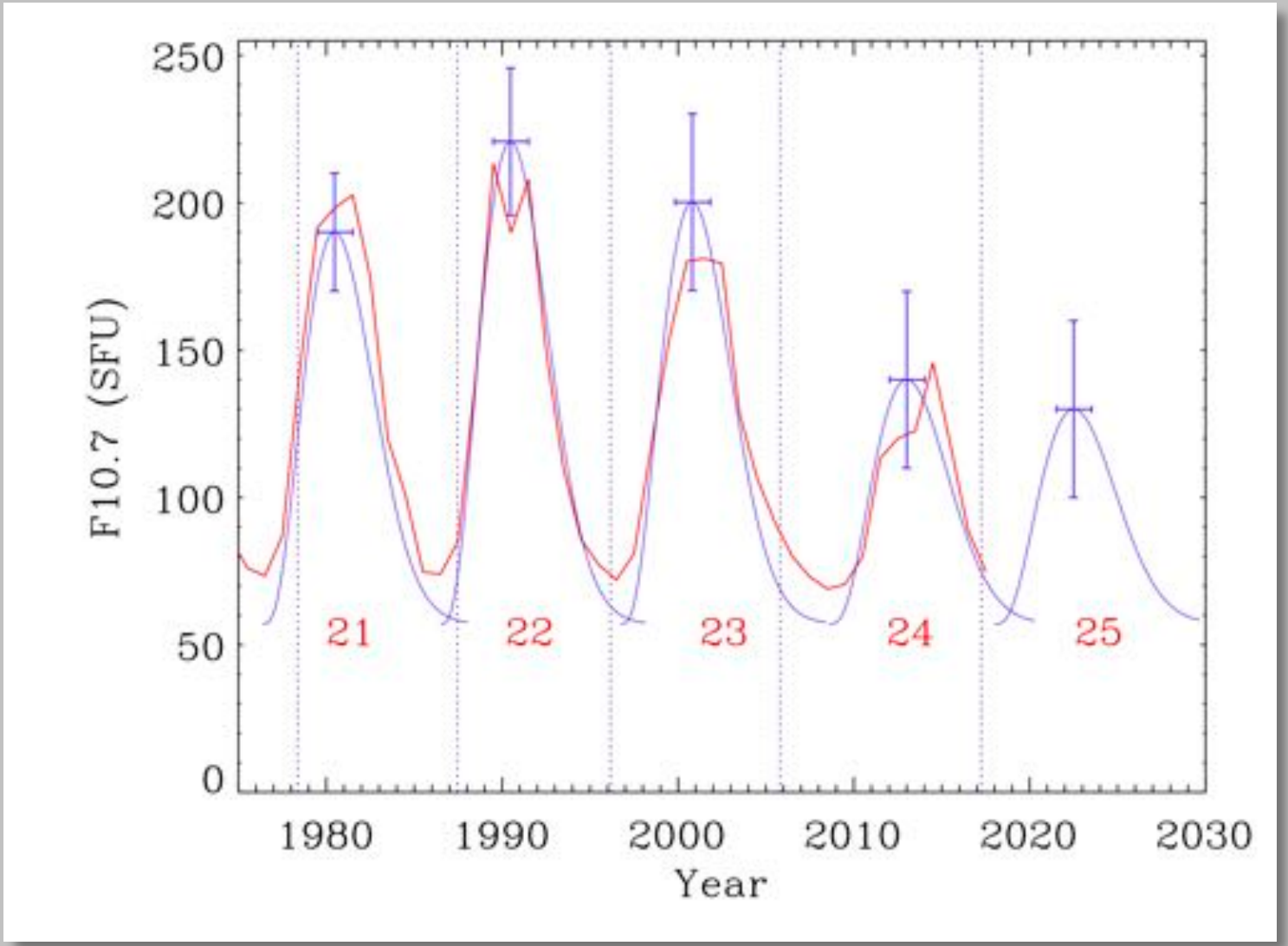
Polar Field Predictions

Blue = predicted

Red = F10.7 (annual)

. . . = date of prediction



Solar activity predictions by Schatten *et al*., have used the polar magnetic field to predict 4 cycles and predict a low Cycle 25.

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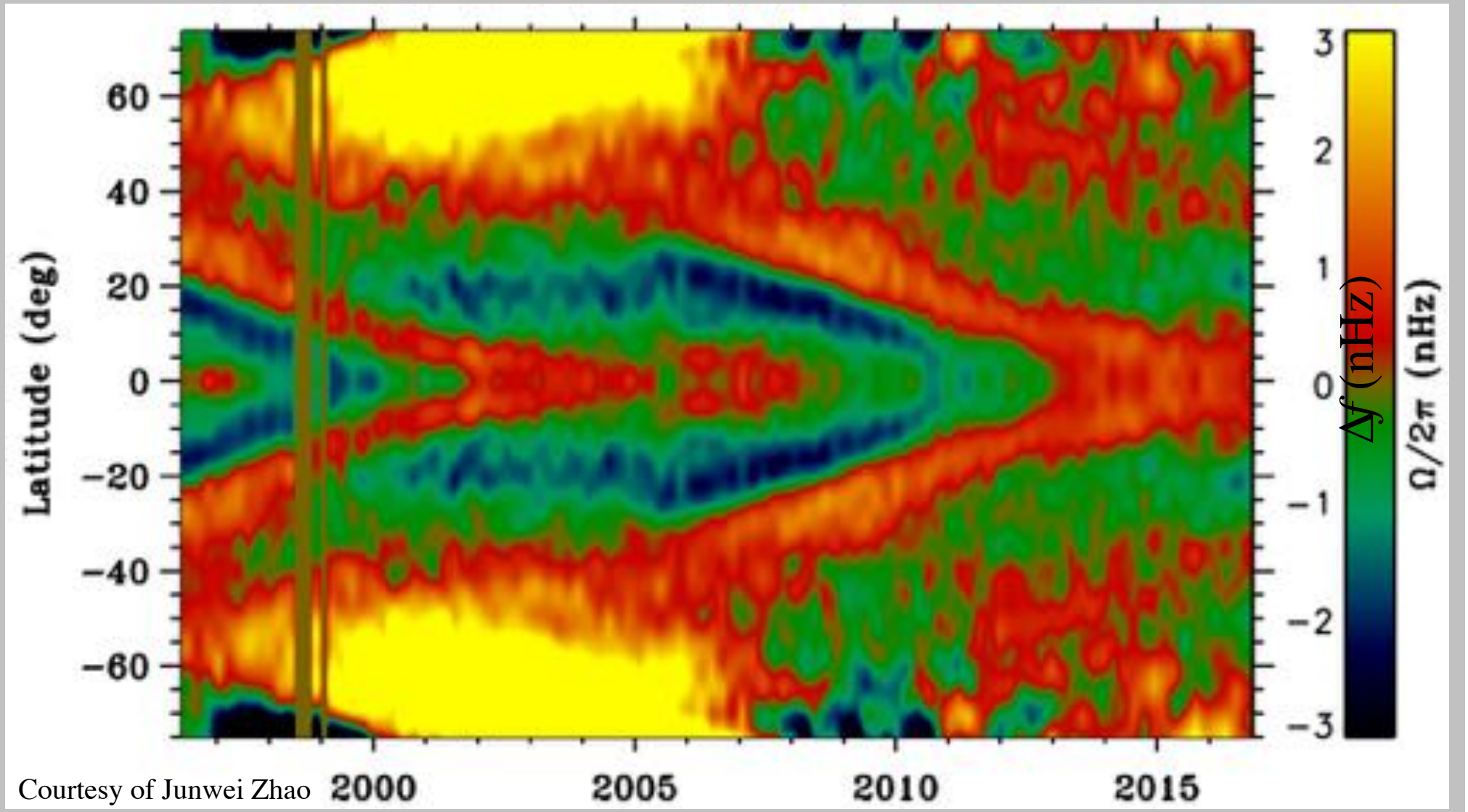
The Future: Flows in the Solar Convection Zone



Courtesy of Junwei Zhao

These near-surface zonal flows have been resolved by helioseismology. They may be a clue to the solar dynamo, at least in the timing of the solar cycle.

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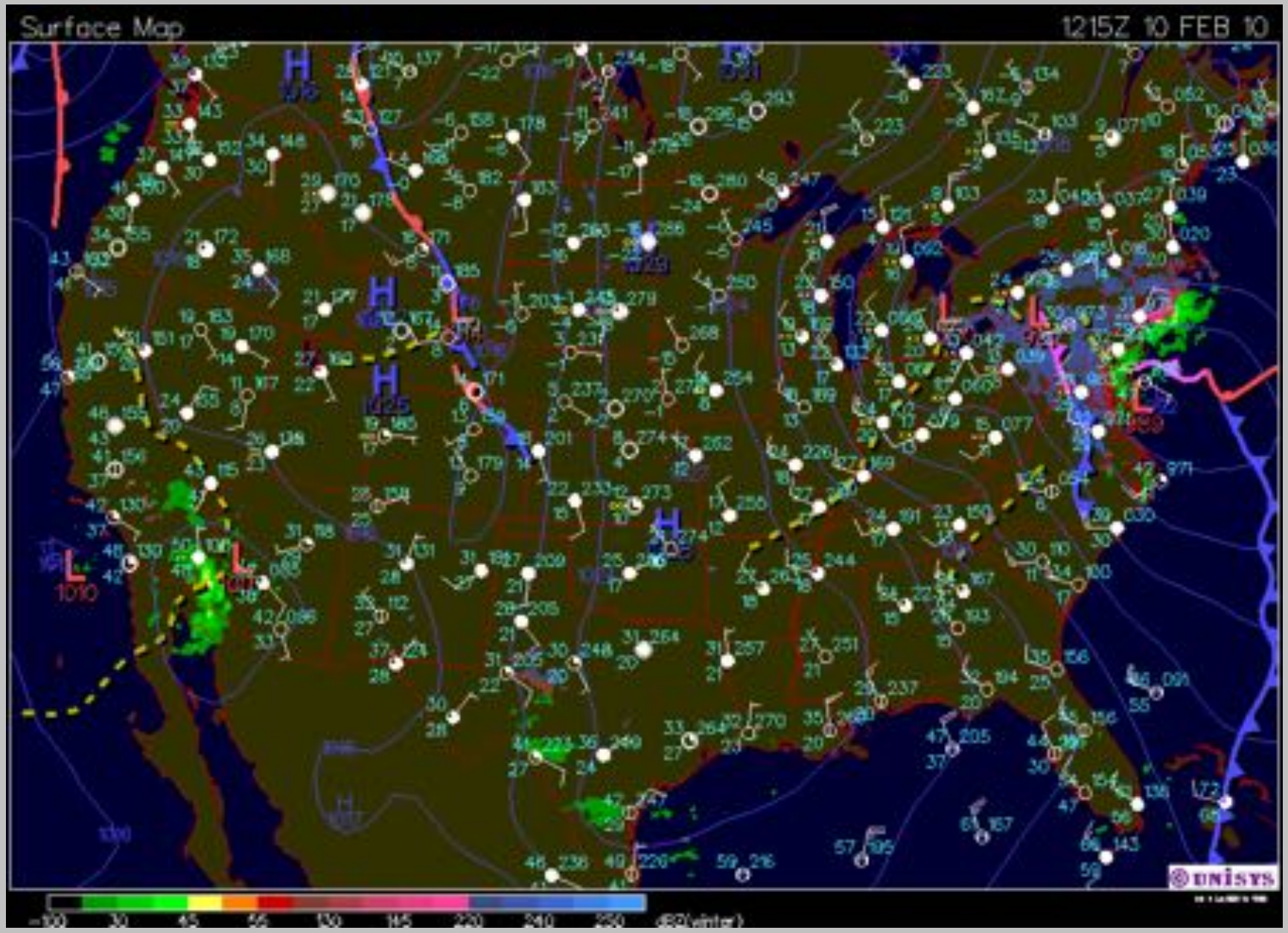
The Future: Solar Dynamo Models in Solar Convection Zone



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The Future: Dynamo Models

- Predictions using various dynamo models appeared first for Solar Cycle 24
- Flux transport models
  - Changes in speed and phasing of meridional transport speed explain differences cycle-to-cycle differences
  - Diffusivities need to be introduced
- Self-consistent nonlinear models are on the horizon
- Relating the internal dynamo to the external observations remains an issue. What is the metric?

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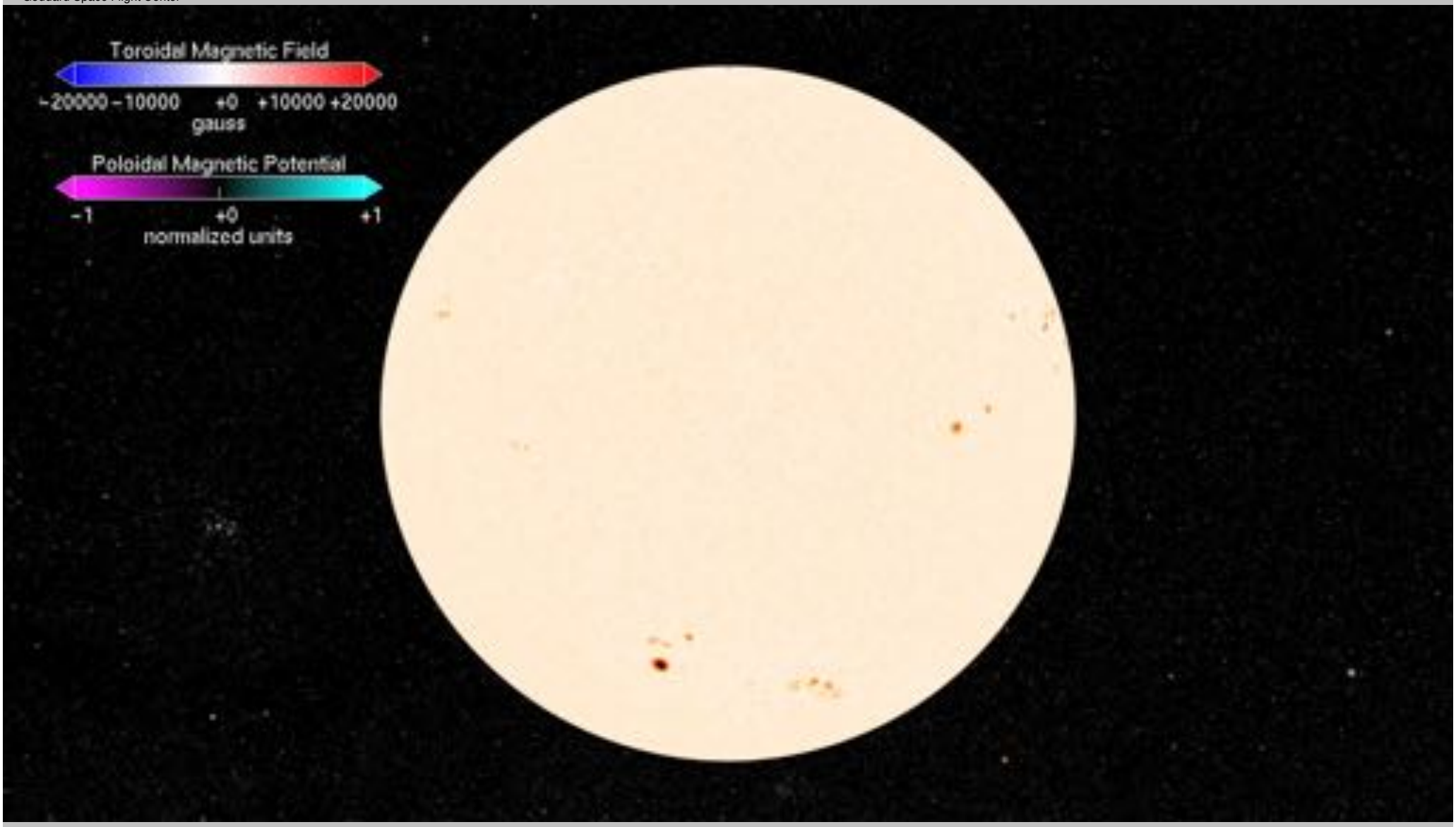
The Future: Dynamo Models



Dynamo model by Nandi, Munoz-Jaramillo, Martens; Visualization Bridgman and Pesnell

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Summary

- Predictions of the sunspot number have been made since the cycle was discovered
- Sunspot number has been used as an example for many types of timeseries analysis, autoregression, chaos
- The solar dynamo is a complex system whose variability is not fully represented by the sunspot number alone. We see coronal holes, high-speed streams, and others that must also be explained. Each type of data can be used to help predict solar activity

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Summary

- Simple timeseries analysis has not produced accurate predictions; additional information is required
- Precursors relate magnetic field at minimum to level of activity at next maximum
- Many models of the solar dynamo exist but none are complete
- We have seen part of the solution: helioseismology and large-scale numerical models
- Solar activity predictions will continue, in research and operational settings

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Future

- Near-real-time models of the solar corona that can predict flares and CMEs (*your jobs!)*
- Helioseismic imaging of active region emergence, subsurface flows, and far-side imaging (*mostly done*)
- Large-scale models of the solar dynamo that track the magnetic dynamo (*continual improvement*)
- Predictions of solar activity at other points in the solar system (*some progress*)
- Exceptional events are always difficult to predict
  - Solar radio bursts that overwhelm GPS (December 6, 2006)
  - Solar particle events that reach Earth without warning (GLEs)
  - Possibility of nonlocal behavior (difficult to assess geo-effectiveness)

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Questions?